

Study on energy conversion characteristics of a high frequency standing-wave thermoacoustic heat engine



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ABSTRACT

A thermoacoustic heat engine (TAHE) is one kind of new power system which can simply convert heat into mechanical power in forms of acoustic wave without any moving mechanical components. This article focuses on using variable acoustical load method to study the energy conversion characteristics of a high frequency standing wave TAHE whose working frequency is around 300 Hz. The coupling relationship between the TAHE and the load is firstly investigated numerically and shows that the output of the TAHE reaches the maximum when the amplitudes of the acoustic resistance and compliance impedance of the load equal. Then, the influence of key parameters of the TAHE, such as the heating power, mean pressure, the dimensions of the stack and resonator on the acoustic power output is analyzed. It indicates that the thermal efficiency of the TAHE could be improved by increasing the mean pressure and the stack length, and by using the tapered resonator. The theoretical analysis and experimental results reported in this work may provide a good reference for building an efficient standing-wave thermoacoustic heat engine with high frequency operation.

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1. Introduction

Increasing concerns on global energy crisis and environmental pollution ignite the enthusiasm for novel and sustainable energy solutions [1]. In the field of power systems, a TAHE might be a promising alternative technology because of its remarkable advantages of environment friendliness, solar power or industrial waste heat utilization and high reliability [2]. A TAHE can find important applications such as refrigeration and power generation [3]. It is quite different from conventional internal combustion engine that certain amount of external heat input into the system could excite intensive spontaneous acoustic oscillation. Thus heat to acoustic power energy conversion is of importance for a TAHE. Much effort has been made to understand the energy conversion characteristics of the TAHE for further improvement of thermal efficiency [4–7]. So far, the most efficient TAHE, i.e. the thermoacoustic-Stirling heat engine achieves an amazing thermal efficiency up to 0.32 [8]. However, much attention has been focused on the relatively large-scale TAHE operated below 100 Hz with an axial length of around 5 m [9], which presents as an obstacle for small-scale applications. One possible option to reduce the system dimension is to increase

the working frequency to several hundred hertz or even higher since the system axial length is roughly proportional to acoustic wavelength.

Besides the above-mentioned thermoacoustic-Stirling heat engine, there is another type of TAHE called standing-wave TAHE. Due to inherent irreversible thermoacoustic conversion processes, standing-wave TAHE is not so efficient as a thermoacoustic-Stirling heat engine. However, its structure simplicity and low maintenance make it still competitive for practical application. Up to now, research on energy conversion characteristics of high frequency standing-wave TAHE is lacking. Therefore, the object of this article is to study the impact of high frequency operation on energy conversion characteristics of a standing-wave TAHE by using variable acoustic load method and further reveal the key parameters those affect the thermal efficiency of the 300 Hz standing-wave TAHE.

2. Numerical results

Fig. 1 shows the schematic drawing of a 300 Hz standing-wave TAHE and its detailed dimensions are listed in Table 1. As depicted in Fig. 1, the 300 Hz standing-wave TAHE consists of a hot buffer, a heating block, a stack, an ambient heat exchanger (HX) and a resonator. The engine converts heat into acoustic power in the stack. Small amount of acoustic power is dissipated in the hot buffer and

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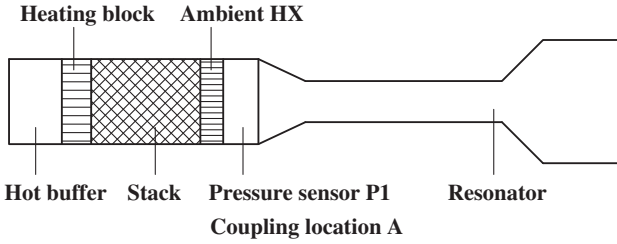


Fig. 1. Schematic drawing of the 300 Hz standing-wave TAHE.

Table 1
Dimensions of the 300 Hz standing-wave thermoacoustic heat engine.

Components	Dimensions
Hot buffer	I.d. 50 mm, length 30 mm
Heating block	I.d. 50 mm, length 20 mm
Stack	I.d. 50 mm, length variable, stainless steel stack with spacing 0.3 mm
Ambient HX	I.d. 50 mm, length 15 mm
Resonator	Cylindrical: mainly i.d. 29 mm length 700 mm tube + i.d. 59 mm length 290 mm tube Tapered: mainly 450 mm cylindrical tube + 400 mm tapered tube (29–71.8 mm i.d.) + 151 mm i.d. spherical vessel

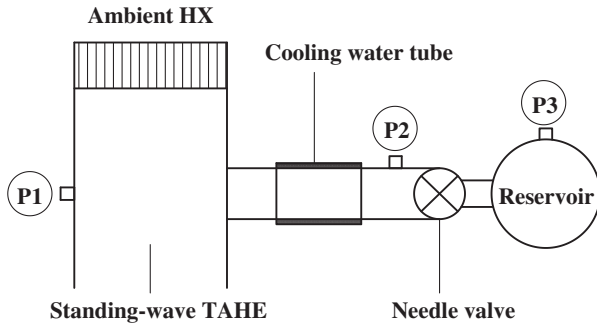


Fig. 2. Schematic drawing of acoustic power output measurement. P_1 , P_2 and P_3 are pressure sensors.

most of the acoustic power transfers to the resonator. Based on the acoustic field of the engine, Location A, which is adjacent to the ambient HX in the resonator, is chosen for the acoustic power output since it has the largest output acoustic power therein. Due to that volume flow rate is quite difficult to be measured experimentally, the variable acoustic (R–C) load method [5,10] is used for acoustic power calculation and measurement instead of measuring the volume flow rate. Fig. 2 displays the schematic drawing of the R–C load, which contains a connecting tube, an adjustable needle valve and a reservoir. The volumes of the reservoirs are variable, ranging from 10 cm³ to 90 cm³. The length of the connecting tube is 50 mm. Note that the thin connecting tube will show strong acoustic inertance effect, which should be taken into account in the computations.

Meanwhile, the R–C load is modelled as lumped elements in calculations due to its much smaller length. According to acoustical-electrical analogy, the needle valve acts as an acoustical resistance while the reservoir as a compliance impedance

$$Z_c = \frac{1}{i\omega C} \quad (1)$$

$$C = \frac{V}{\gamma P_m} \quad (2)$$

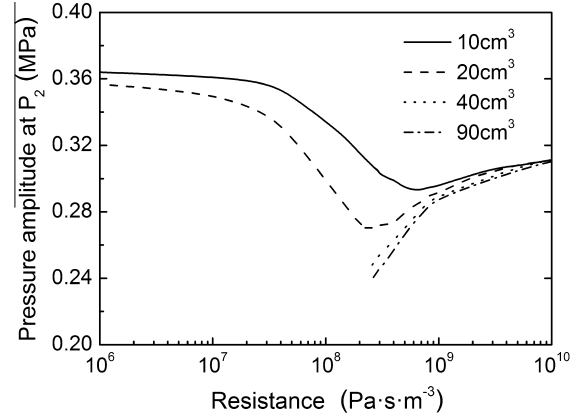


Fig. 3. Pressure amplitude at P_2 vs. resistance.

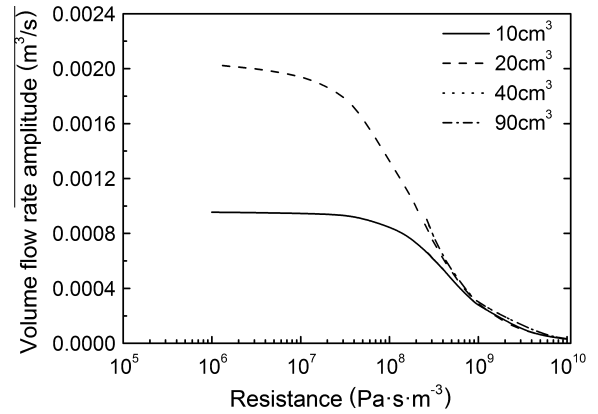


Fig. 4. Volume flow rate vs. resistance.

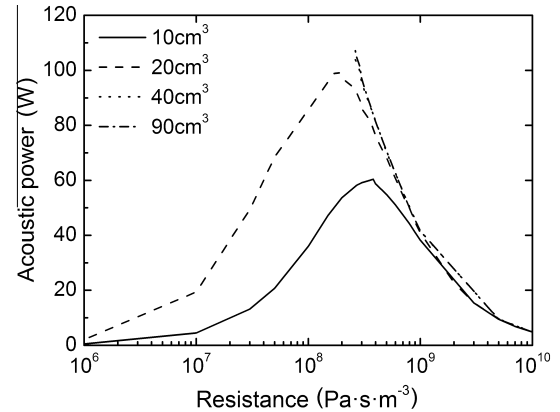


Fig. 5. Output acoustic power vs. resistance.

where ω , C and V denote angular frequency, compliance and reservoir volume, respectively, γ is the specific heat ratio and P_m is the mean pressure. The volume flow rate through the needle valve and the acoustic work dissipated through the valve can be obtained as

$$U_{load} = \frac{P_3 - 0}{Z_c} = \frac{i\omega V P_3}{\gamma P_m} \quad (3)$$

$$\begin{aligned} W_{load} &= \frac{1}{2} \text{Re}[P_2 \cdot U_{load}^*] = \frac{\omega V}{2\gamma P_m} \text{Im}[P_2 \cdot P_3] \\ &= \frac{\omega V}{2\gamma P_m} |P_2| |P_3| \sin \theta_{P_2 - P_3} \end{aligned} \quad (4)$$

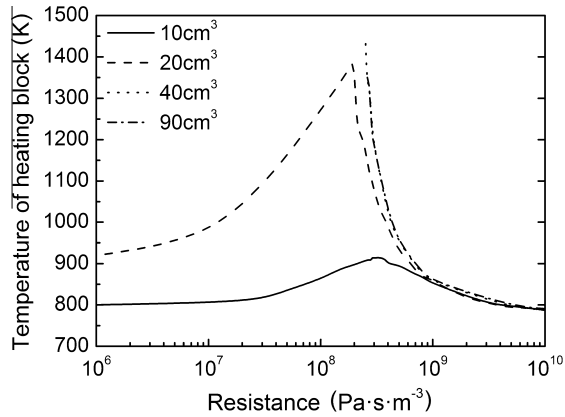


Fig. 6. Heating block temperature vs. resistance.

where P_2 and P_3 are dynamic pressures at the inlet of R–C load and reservoir respectively, and $\theta_{P_2-P_3}$ is their phase difference. Obviously, W_{load} is the acoustic power output of the TAHE.

With the above analyses and appropriate numerical treatments of the R–C load, extensive calculations are performed by using modular program [11] based on linear thermoacoustic theory. 4.2 MPa helium gas, 750 W heating power and a cylindrical resonator are used in calculations.

Figs. 3–6 illustrate the influences of acoustical resistance on pressure amplitude at the inlet of R–C load, the volume flow rate

amplitude through the valve, the acoustic power output and the heating block temperature, respectively. As seen in the figures, the curves of the pressure amplitude, acoustic power output and heating block temperature reach an extreme value while the volume flow rate increases as the resistance decreases when the resistance is in the range of 10^7 – 10^9 Pa s m^{-3} . Since the compliance impedances of the four reservoir are 3.7×10^8 Pa s m^{-3} , 1.85×10^8 Pa s m^{-3} , 9.3×10^7 Pa s m^{-3} and 4.1×10^7 Pa s m^{-3} , indicating that the peaks are reached when the amplitudes of the resistance and the compliance impedance of the R–C load are equal. Numerical results also indicate that larger reservoir leads to even more acoustic power output and higher heating block temperature but smaller pressure amplitude at the inlet of R–C load. When the reservoir volumes are 40 cm³ and 90 cm³, convergent results are difficult to obtain around the peak, which might be attributed to the divergence of energy equation since the temperature is quite higher than practical operation, thus only the results on the right side of the peak are given in the figures. These results are consistent with those of the TAHEs operated below 100 Hz [6], which indicates that the great increase of operating frequency from far below 100 Hz to 300 Hz has no significant impact on the fundamental energy conversion characteristics of the TAHE.

However, one unique effect that induced by high frequency operating was observed in calculations, which has not yet been reported on the TAHEs operated below 100 Hz. The effect is the impact of reservoir volume on pressure amplitudes at the outlet of the engine, i.e. P_1 and at the inlet of the R–C load, i.e. P_2 . Fig. 7 shows the curves of the pressure amplitudes P_1 and P_2 . Apparently,

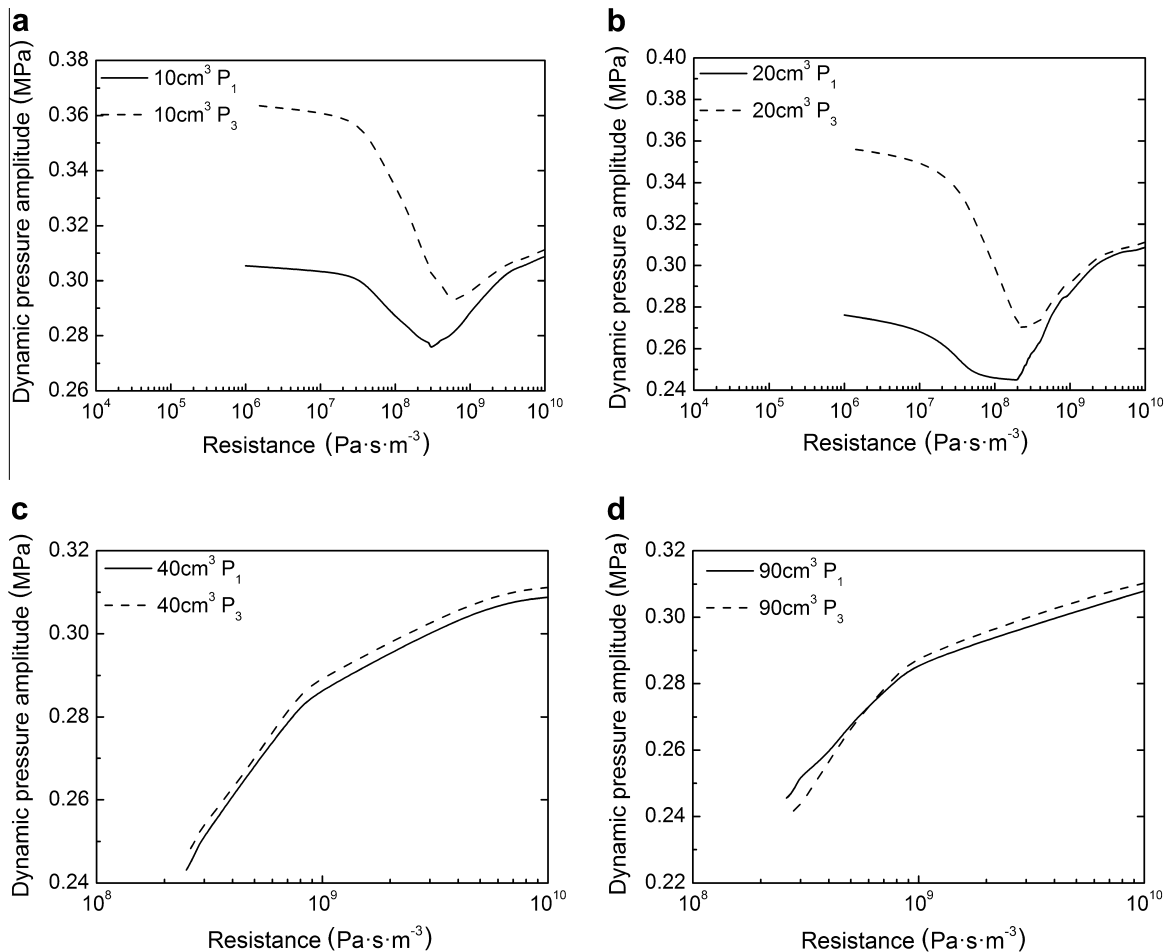


Fig. 7. Pressure amplitudes at P_1 and P_2 vs. resistance. (a) Reservoir of 10 cm³, (b) reservoir of 20 cm³, (c) reservoir of 40 cm³, (d) reservoir of 90 cm³.

when the reservoir volume is smaller than 90 cm^3 , pressure amplitude P_2 is larger than pressure amplitude P_1 , which indicates that the connecting tube acts as an acoustic pressure amplifier tube. Whereas, the amplification ratio defined as $r = P_2/P_1$ decreases when the reservoir volume increases. While the reservoir volume is as large as 90 cm^3 , P_2 becomes smaller than P_1 when the resistance drops below a certain value, which has not been observed in calculations and experiments on TAHs operated below 100 Hz . This effect might be instructive for the designs of acoustic loads such as refrigerator or linear motor since the acoustic impedance of these loads mainly behaves as acoustic resistance and compliance, and the compliance should not be too large, otherwise, the inlet pressure amplitude of the loads will weaken.

3. Experimental verification and discussion

In order to validate the calculations and further study the key parameters which influence the output performance, lots of experiments were carried out. The experimental set-up and the measuring system are shown in Figs. 1 and 2. Heater cartridges are used for heat input. Heating power is measured by a power meter. Calibrated armoured K type thermocouples are adopted to measure the temperature of heating block. For safety operation, the heating block temperature is controlled below 650°C . Three high precision piezoelectric pressure sensors (PCB), i.e. P_1 , P_2 and P_3 , are mounted in the system. A self-made needle valve with neglectable dead volume is applied, and a cooling water tube made of copper is wrapped outside the valve to make it work around ambient temperature. All the pressure and temperature data are acquired through clips supplied by NI and processed and displayed with self-developed programs based on Labview 7.1 [12].

For all the experiments, helium gas is used. Since the dead volume of the connecting tube and needle valve is close to 1.5 cm^3 , the reservoir whose volume is 10 cm^3 is not appropriate for the experiments, moreover, as shown in the calculations that larger volume reservoir could output more acoustic power, hence a reservoir of 90 cm^3 is used in the experiments.

Figs. 8–10 give the influences of the mean pressure, stack length and resonator on the acoustic power output, respectively. According to thermoacoustics, acoustic power is proportional to gas density, thus it could be seen in Fig. 8 that with the same heating power of 750 W , higher mean pressure leads to larger output acoustic power. With respect to the impact of stack length as depicted in Fig. 9, also with the same heating power of 750 W , a shorter stack results in larger output acoustic power for the same heating temperature. However, the shorter stack can damp the spontaneous oscillation as the acoustical resistance of the needle valve decreases. In addition, failure in oscillation has also been detected when the stack length is 90 mm . As seen in the figure, an optimum stack length might be around 80 mm to obtain a largest output acoustic power given the conditions of 750 W heating power and highest heating block temperature of 650°C for safety operation. As known, the resonator shape plays an important role in determining the performance of TAHs [9,13]. Obviously, the resonator shape does affect the acoustic power output. As seen in Fig. 10, for the same heating block temperature, more output acoustic power is achieved by using a tapered resonator, furthermore the net output efficiency with the tapered resonator is even higher than that with a cylindrical resonator by more than 10% . So far, the highest net output efficiency reaches up to 9% .

As stated in the calculations that when the reservoir volume smaller than 90 cm^3 , the connecting tube behaves as an acoustic pressure amplifier tube, i.e., P_2 is larger than P_1 as shown in Fig. 11. However, while the reservoir volume is as large as

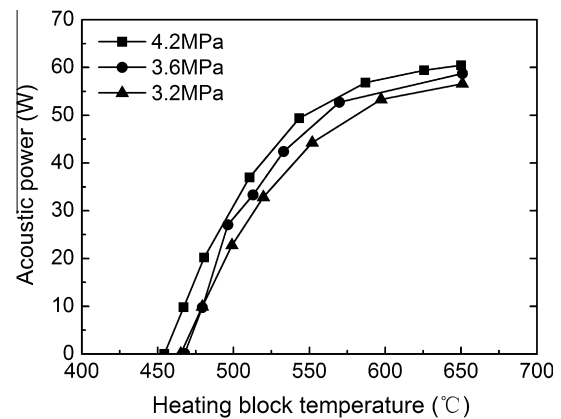


Fig. 8. Influence of mean pressure on acoustic power output.

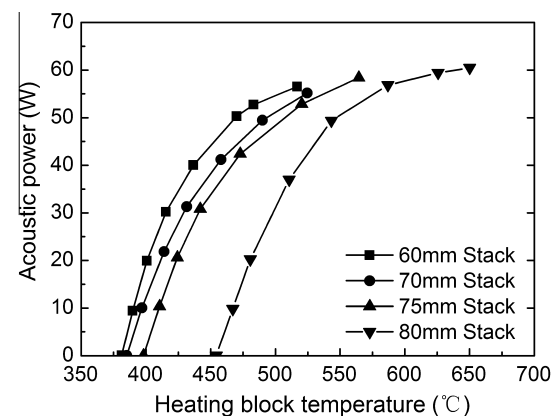


Fig. 9. Influence of stack length on acoustic power output.

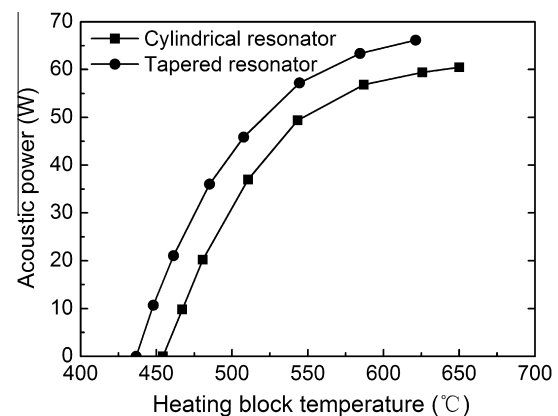


Fig. 10. Influence of resonator on acoustic power output.

90 cm^3 , P_2 becomes smaller than P_1 once the acoustical resistance of the needle valve drops below a certain value, which is also observed in the experiments as illustrated in Fig. 12. The calculated and experimental results are in reasonable agreement. It should be noted that the internal mechanism is quite complicated that other factors such as the operating frequency, the connecting tube and minor loss might influence its behaviour, which requires even deeper understanding. Furthermore, it can be seen in Fig. 13 that the experimental acoustic power output increases with the decrease of resistance impedance, agreeing well with the calculated

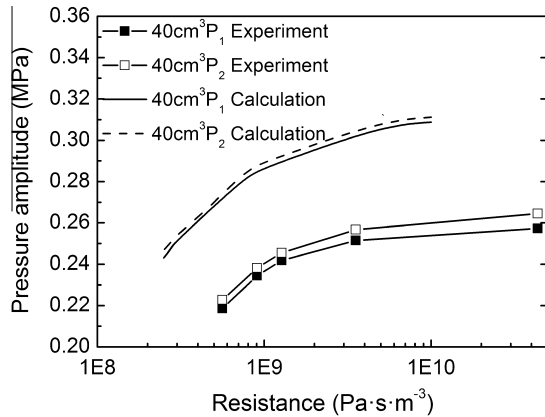


Fig. 11. Comparison of pressure amplitudes at P_1 and P_3 with reservoir of 40 cm^3 .

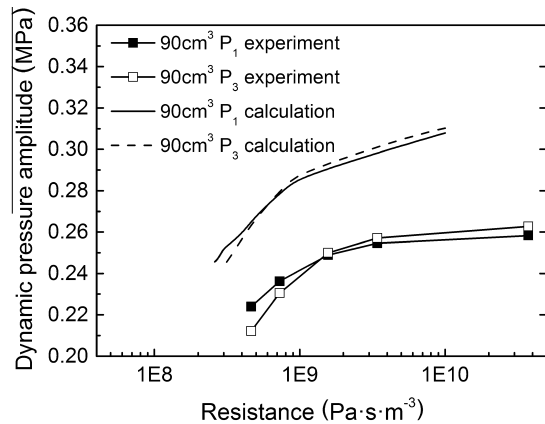


Fig. 12. Comparison of pressure amplitudes at P_1 and P_3 with reservoir of 90 cm^3 .

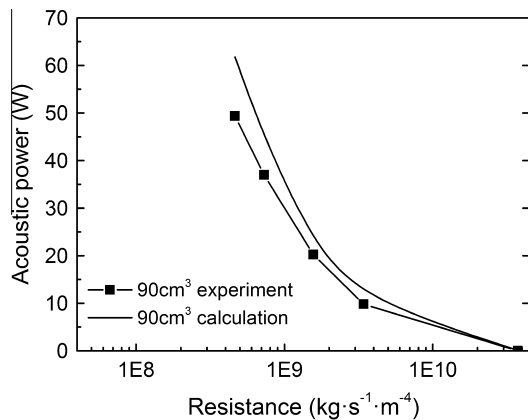


Fig. 13. Numerical and experimental comparison of acoustic power.

results, especially when the resistance impedance is getting larger. The deviation might be mainly the results of minor loss that

proportional to the square of volume flow rate and the unpredictable nonlinear effects.

4. Conclusion

The energy conversion characteristics of a 300 Hz standing-wave TAHE has been studied numerically and experimentally. The calculations indicate that high frequency operation has no significant influence on the fundamental energy conversion characteristics. When the amplitudes of the acoustic resistance and compliance impedance of the R - C load equal, a highest exportable acoustic power could be achieved. However, the compliance of the R - C load would seriously affect the pressure amplitudes at the outlet of the engine and the inlet of the R - C load under high frequency operation, which has been verified in the experiments. This observation might be instructive for the design of acoustic load appropriate for a specific high frequency TAHE. Furthermore, the experimental results reveal that the system thermal efficiency is greatly influenced by the mean pressure, the stack length and the resonator. Increasing the mean pressure and the stack length, and by using the tapered resonator could effectively improve the thermal efficiency.

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